NEW TECHNOLOGIES FOR REDUCING AVIATION WEATHER-RELATED ACCIDENTS

H. Paul Stough, III*, James F. Watson, Jr.*, and Michael A. Jarrell**
***NASA Langley Research Center, **NASA Glenn Research Center**

Keywords: aviation, safety, weather, turbulence, data link, cockpit systems

Abstract

The National Aeronautics and Space Administration (NASA) has developed technologies to reduce aviation weather-related accidents. New technologies are presented for data-link and display of weather information to aircraft in flight, for detection of turbulence ahead of aircraft in flight, and for automated in-situ reporting of atmospheric conditions from aircraft.

1 Introduction

In February 1997, a U.S. goal was established to reduce the fatal accident rate for aviation by 80% within ten years. Weather, a causal factor in 30% of all aviation accidents, was identified as a key area to be addressed. NASA established an Aviation Safety Program (AvSP), to develop technologies needed to help the Federal Aviation Administration (FAA) and the aviation industry achieve the national safety goal. Within the AvSP, a Weather Accident Prevention Project was created to develop new capabilities to reduce weather-related accidents. Many of these accidents have been attributed to a lack of weather situation awareness by pilots in flight. Improving the strategic and tactical weather information available and its presentation to pilots in flight can enhance weather situation awareness and enable avoidance of adverse conditions.

New technologies have been developed for cockpit presentation of graphic weather information, for turbulence prediction and warning, for automated airborne in-situ weather reporting, and for data linking of weather information between airplanes in flight and providers and users on the ground [1-4]. This paper describes these technologies developed by NASA in partnership with the FAA, National Oceanic and Atmospheric Administration (NOAA), industry and the research community.

2 Cockpit Weather Information Systems

Deteriorating weather conditions are frequently the cause of changes in flight objectives, and the pilot needs to know quickly where the weather is better and what to do to get there. An aviation weather information (AWIN) system (Fig. 1) consists of weather products, a means for distributing the products to the users, and a means to present the information to the users. However, pilots need more than just weather information for in-flight decision making. This includes aircraft capabilities, pilot capabilities, and information on flight-path-relevant terrain, obstacles, air space restrictions, and traffic. Data links are needed to exchange information between airplanes and ground stations. Aircraft-to-aircraft links may be needed for timely exchange of in situ weather reports. Information from onboard sensors may be passed to ground-based weather systems for incorporation in updated forecasts and reports that can be subsequently transmitted to aircraft in flight. Data-link weather information systems are intended to provide information for long-term strategic planning and to augment onboard sensors such as weather radar and lightning detectors. NASA efforts have addressed U.S. national data-link weather information capabilities for general aviation (GA), and both national and worldwide capabilities for transport

aircraft. Both installed and portable weather display technologies have been evaluated to meet the needs of these different user groups.
The timeliness, accuracy and presentation of cockpit weather information need to support decisions that result in safe and efficient actions.

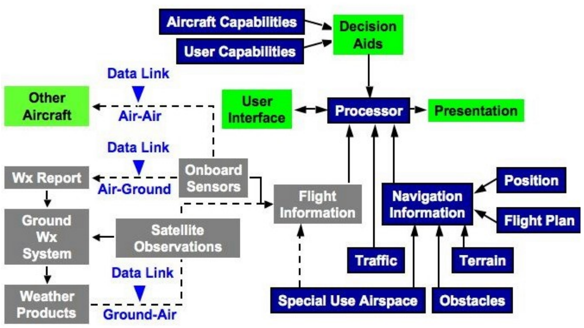

Fig. 1. Block Diagram of an AWIN System

2.1 First-Generation Systems

In 1998, NASA initiated cooperative research efforts with industry-led teams to "jump start" the development and implementation of AWIN systems. These end-to-end systems were demonstrated through prototypes and in-service evaluations with teams led by Boeing and Honeywell for worldwide transport operations and ARNAV Systems and Honeywell-Bendix/King for U.S. national general aviation operations. These “first generation” systems utilized existing weather products reformatted for data link and display in the cockpit. This work was leveraged by the FAA to create a Flight Information Services Data Link (FISDL) system that provides data-link weather nationwide in the U.S. This FISDL system achieved operational status in early 2002.

Honeywell International, in a joint effort with NASA, developed a Weather Information Network (WINN) capable of providing graphical weather information to the cockpit of commercial and business aircraft flying worldwide. The network included airborne displays, airborne and ground-based servers, and multiple providers of weather products and data-link services. An open architecture was adopted to accommodate any kind of data-link technology. Both a satellite-based link and a terrestrial very high frequency/ultra-high frequency (VHF/UHF) telephone link were evaluated. Several different types of weather information could be overlaid or viewed individually. During the winter of 2001, United Air Lines conducted over 40 in-service evaluation (ISE) flights with the WINN system incorporated in a prototype electronic flight bag (Fig. 2). Weather products were delivered to the airplane via a GTE Airphone and included airport observations (METARs), terminal area forecasts (TAFs), ground weather radar reflectivity (NEXRAD), turbulence, significant weather cautions (graphic SIGMETs), and satellite cloud images. An average of 1 to 2 % time savings (and thus cost) per leg was attributed to increased weather situation awareness. A potential reduction in Aircraft Communications Addressing and Reporting System (ACARS) messaging traffic (and thus cost) of 40 to 50% was estimated.

Fig. 2. UAL WINN ISE

In the U.S., data-link cockpit weather information systems have now become a commercial off-the-shelf item, especially for general aviation. A variety of display devices and information delivery architectures are being employed to address the varied needs of GA operators. The FAA recently began implementation of a U.S. national Universal Access Transceiver (UAT) network for provision of traffic and flight operational information, including weather, data-linked to the cockpit of equipped aircraft.

2.2 Weather Information Presentation

NASA has examined how data-linked weather information can best be used with other existing weather information available to pilots in flight. On-board weather radar, lightning detection systems, in situ reports from other aircraft and information from collaboration with ground weather briefers need to be combined effectively with the products delivered to the pilot via data-link. Means need to be developed to help pilots search the information sources available, identify trends and changes affecting their flight, and make timely decisions to avoid hazardous weather.

Formats for cockpit presentation of textual and graphic weather information have been studied for their effects on pilot navigation decisions. These studies showed the need to display the airplane's position as part of graphic weather depictions; to provide an indication of distance or range; and to present the age rather than the time of the weather information. The resolution of graphic depictions of data-linked next generation radar (NEXRAD) was shown to affect pilot navigation decisions in adverse weather situations. When resolution of NEXRAD images was increased, i.e. each pixel represented a smaller area, pilots were more likely to continue their flights with the expectation that they could fly around or between significant weather. The best in-flight convective weather situation awareness was achieved when multiple weather information sources (out-the-window view, radio voice communication, and data-link display) were used together.

Trend information presented via looping of NEXRAD images and display of the National Convective Weather Forecast product was found to provide a significant increase in situation awareness to the pilot with respect to location, proximity, and direction of movement of convective weather. However, over-reliance on the information presented by the data-link system at the expense of accessing more conventional sources of information such as Flight Service Stations (FSS) was found to offset the improved situation awareness to the extent that decision making was no different with or without the cockpit weather display.

Flight crew trust of cockpit weather information and reaction as a team to displays of impending adverse weather have been studied. Crews trusted onboard weather radar more than data-linked information. When both systems agreed, crews' trust of the data-linked weather display increased. When the onboard and NEXRAD displays did not agree, the crews trusted the onboard radar more, but still used the NEXRAD to augment their overall situation awareness. Crews were more likely to make correct deviation decisions when the NEXRAD system depicted the impending adverse weather.

2.3 Next-Generation Systems

NASA, Georgia Tech Research Institute, and Rockwell Collins developed a prototype AWIN system with the capability to combine information from both on-board sensors and data-links and to display graphical and textual weather information to the pilots. This Airborne Hazard Awareness System (AHAS) can automatically parse text and weather data, convert it to graphics, evaluate both tactical and strategic hazards in the weather data stream and provide alerts to pilots. Weather products include visibility, ceiling, winds, gusts, precipitation, thunderstorm proximity and severity, storm tops, hail, icing and turbulence. Hazards assessed include proximity of SIGMETs en route, winds aloft en route, projected thunderstorm intercept, remarks from pilot reports (PIREPs) and METAR stations along the flight plan, and crosswinds, ceiling and visibility at the destination airport. AHAS strategic and tactical displays are shown in Fig. 3 and 4. In a simulator experiment, pilots were more likely to make correct deviation decisions with the AHAS integrated tactical display of on-board weather radar and data-linked NEXRAD. Greater situation awareness, lower workload, and ability to make weather decisions sooner were also attributed to the integrated display.

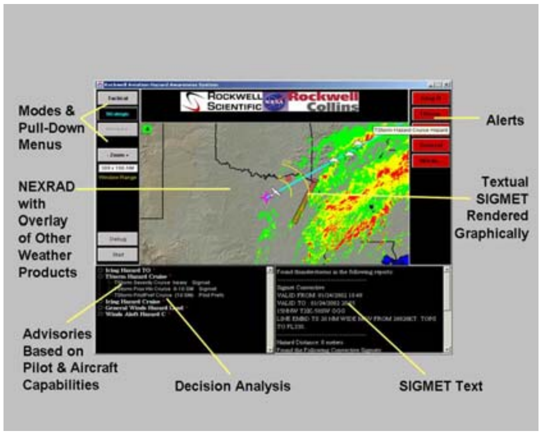

Fig. 3. AHAS Strategic Display

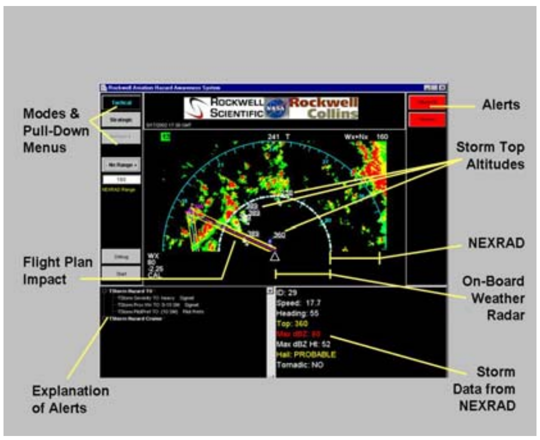

Fig. 4. AHAS Tactical Display

3 Turbulence Prediction and Warning

Aircraft encounters with atmospheric turbulence are the leading cause of injuries to transport aircraft passengers and crews. Cabin occupants who are seated with their seat belts securely fastened are rarely injured in turbulence encounters. If the pilot receives a timely and reliable turbulence alert, passengers and flight attendants can be warned and securely seated; thereby, removing them from the risk of injury.

3.1 Enhanced Turbulence Radar

About 75% of turbulence encounters occur near significant convective activity, even though the aircraft may have been out of the clouds. Existing airborne wind shear radars possess reflectivity-detection and signal-processing capabilities that can be utilized to enable look-ahead turbulence detection and hazard prediction in these conditions. A NASA-industry team has developed an airborne radar unit with turbulence detection algorithms and validated its performance through flight tests on NASA's Boeing 757 (B-757) research airplane. Algorithms in the research radar unit statistically predict atmospheric spectral width (deviation in Doppler velocities) using multiple radar antenna scans, compute the airplane's anticipated response to the encounter, and generate a near-real-time hazard level display.

Atmospheric conditions of past turbulence encounters that resulted in passenger or crew injuries were modeled and served as validation cases for this prediction technology. Flight tests, which compiled 55 turbulence encounters, validated the research concepts and indicated that moderate-to-severe turbulence hazards to the aircraft could be predicted with 80% confidence and at least a 90 second warning time could be provided for radar reflectivity levels above 15dBz. Because the same atmospheric turbulence will produce widely varying aircraft response depending upon aircraft type, weight, configuration, and flight conditions, aircraft-specific hazard tables were developed using aircraft flight simulators for eight different jet transports. This enables radar manufacturers and turbulence algorithm developers to relate the spectral width radar parameter to actual aircraft response.

The radar development team partnered with Delta Air Lines (DAL) for an ISE of the airborne radar incorporating the enhanced turbulence mode. A commercial airborne weather radar with automated antenna multi-scan capability was modified with updated algorithms for spectral width radar signal processing, a B-737-800 turbulence hazard algorithm, a data bus flight parameter interface, a data logger, and a turbulence color display capability. The prototype radar unit received FAA certification and was installed on a DAL B-737-800 in 2004. This prototype Enhanced-Turbulence (E-Turb) Radar provides turbulence hazard prediction capability extending at least

25nm ahead of the aircraft. Two levels of magenta are used on the radar display (Fig. 5) to indicate turbulence hazards – speckled magenta for "ride quality" (light turbulence), and solid magenta for the need to "secure the cabin" (moderate to severe turbulence).

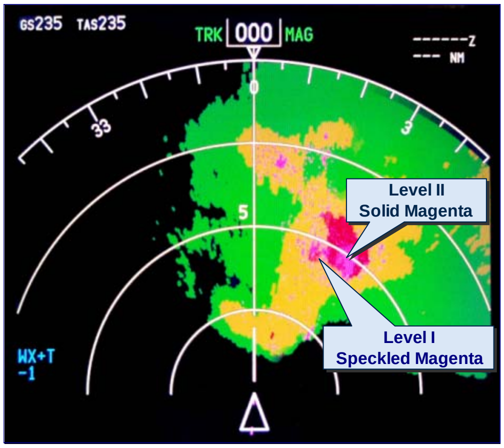

Fig. 5. Cockpit Radar Display of Turbulence

From 3000 flight hours of data collected between August 2004 and March 2006, 917 turbulence events were identified and analyzed. Of these, 92 events occurred with no radar display of predicted turbulence, but the aircraft experienced turbulence. These appear to be atmospheric conditions with reflectivity signal levels too low for radar processing. There were 402 events where the radar displayed regions of turbulence, but the aircraft did not penetrate the region. There were 423 events where the aircraft displayed turbulence and penetrated the region, including instances of turbulence at 4dBz reflectivity level. A statistical analysis of radar-predicted accelerations and measured accelerations for these 423 events indicates that the E-Turb Radar produces reliable predictions within a 95% confidence interval.

Seventy-seven percent of flight-crew-evaluation responses indicated an accurate correlation between E-Turb Radar predictions and actual encounters. Some crews noted that "light chop" encountered in clouds did not appear on the display; however, analyses indicated that the predicted hazard levels were below the "ride quality" threshold. There were many instances where the crews used the E-Turb Radar display for course change requests, and several instances of encounters when denied. Overall, flight crews were impressed with the accuracy and range of turbulence prediction provided, particularly in areas of low radar reflectivity, and liked the intuitiveness of the two-level display.

To facilitate certification of airborne turbulence detection systems, a tool set was developed that enables a turbulence prediction algorithm to be tested via simulation of an airplane flight path through known atmospheric turbulence, and the output of the algorithm to be displayed and scored [5]. A three-year project is now underway by the FAA to further develop E-Turb Radar certification standards and guidance.

3.2 Automated Turbulence Reporting

Currently, turbulence encounter reporting depends primarily on PIREPs passed from the cockpit to controllers, briefers, and dispatchers via voice communications. These "ride reports," however, do not produce consistent, accurate, and timely reports of the location and severity of aircraft-encountered turbulence.

The airplane turbulence response algorithms developed for evaluating the E-Turb Radar performance provide a basis for an automated turbulence encounter reporting system. Acceleration-based thresholds were established for triggering turbulence reports, and the resulting information was packaged into a message for automatic transmission to other airplanes aloft and to airline operations centers with sufficient timeliness to benefit turbulence avoidance decisions. This capability, designated Turbulence Auto PIREP System (TAPS), provides timely and accurate reporting of turbulence encounters.

In 2004, a TAPS ISE was undertaken in partnership with DAL. Aircraft were TAPS enabled with the software residing in the Aircraft Condition and Monitoring System. TAPS reports were transmitted via ACARS

from the aircraft, were integrated into the Web Aircraft Situation Display flight following package, and displayed as shown in Fig. 6 to dispatchers within the DAL operations center. By September 2004, all 71 DAL B-737-800 aircraft were TAPS enabled and sending reports to the airline operations center. During 2005, TAPS equipage was expanded to include all 31 DAL B-767-300ER and 21 B-767-400ER aircraft that typically fly oceanic routes.

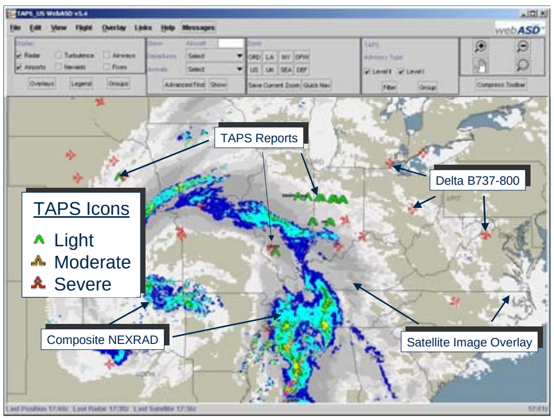

Fig. 6. TAPS Ground Station Display

From June 2004 through April 2006, 62,415 TAPS reports were transmitted to the operations center, including 135 "severe", 1697 "moderate", 44,578 "light" and 16,005 "less than light" reports. Fig. 7 shows the monthly frequency of turbulence encounters per aircraft. Seasonal variation of turbulence encounters is evident. On average there were 35 TAPS reports per airplane per month. Thus, TAPS communication needs are negligible compared to the routine volume of operations, weather, and maintenance ACARS messages.

Sixty-one PIREPs of "moderate-or-greater" encounters were made from TAPS equipped aircraft. A comparison to TAPS reports from the flights indicated that 29% of the PIREPs agreed with TAPS in severity levels, 48% had severity greater than TAPS reports, 7% had severity less than TAPS reports, and 15% had no TAPS reports at all. Overall, the PIREPs underreported the occurrence of turbulence and overstated its severity. Accurate turbulence reporting also identifies which aircraft actually need severe loads maintenance inspections and provides data for injury investigations. Fig. 8 illustrates extreme cases of TAPS-PIREPs comparisons.

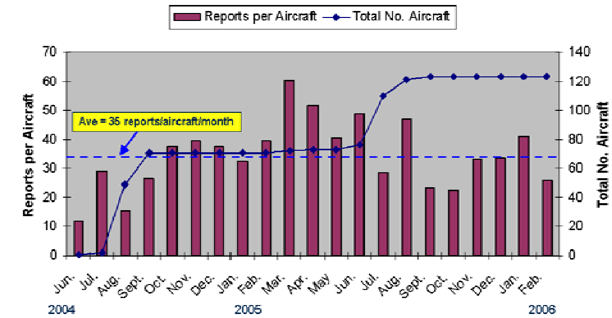

Fig. 7. Monthly TAPS Reporting

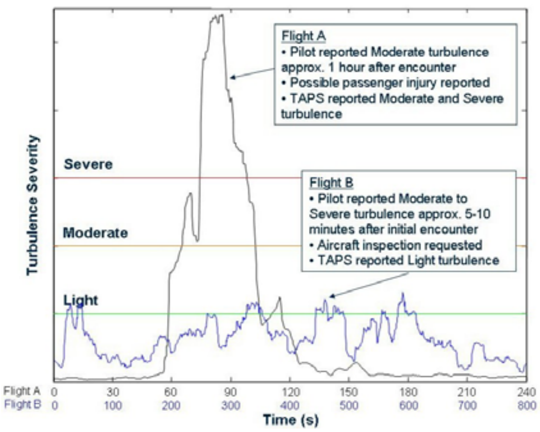

Fig. 8. Two Comparisons of PIREPs vs. TAPS

Many DAL flight crews began inquiring as to availability of recent TAPS reports for encounters that they heard reported over the radio and reports from aircraft near or ahead of their flight path. This prompted several dispatchers to start "relaying" moderate-or-greater TAPS reports to applicable aircraft. The development of a TAPS cockpit display and capability for TAPS reports to be transmitted to near-vicinity or following aircraft is anticipated in the future. With this capability, the location and severity of turbulence encountered by aircraft will be readily available to flight crews, in addition to dispatchers and maintenance organizations, for increased safety and efficiency of operations.

4 Automated Airborne Weather Reporting

A key to safer and more efficient operations is knowing where the hazardous weather is

(observations) and where it's going to be in the future (forecasting). Improved forecasting and dissemination of hazardous weather locations enables aircraft operators to strategically avoid atmospheric hazards such as icing, turbulence, and thunderstorms, thus improving aviation safety and efficiency. Most of the moisture, a key factor in hazardous weather development, is at altitudes below 25,000 ft., and existing observation systems provide few, sparse data in this region. Currently, the Meteorological Data Collection and Reporting System (MDCRS) collects position, temperature and wind data transmitted to the ground from participating jet transport aircraft and sends the information to the U.S. National Weather Service (NWS) for input to forecast models. Because these airplanes operate into and out of only about sixty major airports in the U.S., the atmospheric soundings are limited to these locations. At cruise altitudes, observations are high above most of the adverse weather.

Aircraft operating at the lower altitudes and frequenting smaller airports have the potential to make a significant contribution to improving weather products through the collection and dissemination of in-flight weather observations. Implementation of an automated, in situ, airborne weather reporting system using these airplanes will require viable sensors and an extensive data-link communication network.

4.1 Sensor System

NASA has worked with the FAA, NWS, industry, and research community to develop automated-weather-reporting capabilities for these aircraft. A robust, compact, lightweight, integrated sensor system, referred to as a Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor, has been developed to automatically measure and report humidity, pressure, temperature, wind, turbulence, icing, and location from aircraft in flight. Communications architectures and technologies have also been developed for distribution of data to the NWS, FSS, and other aircraft in flight.

The sensor (Fig. 9) consists of a probe (external to the aircraft) and an attached signal processing unit. The probe body has the shape of a symmetric airfoil with span of 4.05 inches and cord of 2.6 inches. Dynamic pressure, sensed via a port protruding from the leading edge, and static pressure, sensed via a port located on the trailing edge of the sensor body, are used to compute indicated and true airspeed. An additional algorithm computes eddy dissipation rate (an aircraft independent measure of turbulence). A flow tube directs air into a sensing cavity containing air temperature and relative humidity sensors. Airflow from the sensor cavity is discharged through holes near the base of the sensor. A leading edge notch incorporates infrared transmitters and detectors for ice detection. A built-in GPS provides time and location for each observation and provides the ground track, which is used with externally provided heading information to calculate winds aloft. The signal-processing unit computes derived parameters from basic measurements. These data are output to a data-link transceiver. All observation intervals are based on static pressure (altitude) with a timed default. This observation protocol is a modification of ARINC 620 Version 4, which is being standardized by the World Meteorological Organization (WMO) Aircraft Meteorological Data Relay (AMDAR) Panel. Special observations are triggered by an icing onset.

Fig. 9. TAMDAR Sensor

4.2 Great Lakes Fleet Experiment

An operational evaluation of TAMDAR capabilities, referred to as the Great Lakes Fleet Experiment, was conducted from January 2005 through January 2006. TAMDAR sensors were installed on 63 Mesaba Airlines' Saab 340 turboprop aircraft flying in the Great Lakes region of the U.S. Each day these aircraft made over 400 flights to 75 airports, and provide more than 800 soundings for a total of over 25,000 daily observations. These observations are significant when compared with the approximately 100,000 daily MDCRS observations of wind and temperature over the entire contiguous U. S.

Forecasters at NWS forecast offices and researchers at the Earth Systems Research Lab are using TAMDAR data and evaluating its impact on weather forecasts. Evaluations include direct comparisons of wind, temperature, and humidity data from TAMDAR with those from radiosondes, and impact on performance of the Rapid Update Cycle aviation weather forecast code. Researchers at the National Center for Atmospheric Research are evaluating the impact of TAMDAR data on the Current Icing Potential algorithm, the prediction of convective precipitation, short-term forecasts of convection, precipitation forecast skill, and turbulence reporting. These evaluations have indicated that TAMDAR is having a positive impact on aviation forecasts.

5 Weather Information Communication

Weather information communications allow the sharing of data and information between the ground and air domains and information transfer between aircraft. Data link characteristics and representative communications links are presented in Fig. 10. Investigations of the communications requirements and associated data-link architectures optimal for the delivery of graphical weather products to GA and commercial-air-transport cockpits established current, mid-term and long-term weather communications requirements.

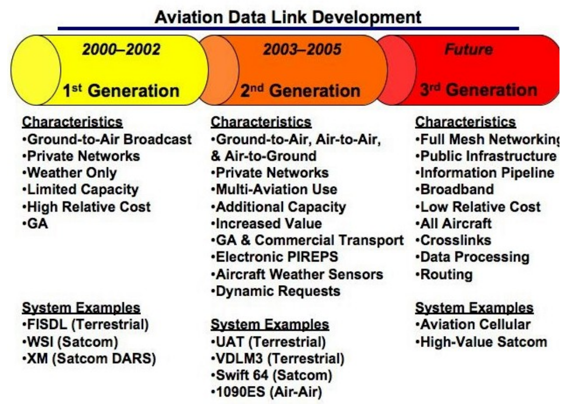

Fig. 10. Data Link

A VHF Data Link Mode 2 (VDLM2) data link operating in the aeronautical VHF frequency band was demonstrated with broadcast data rates up to 31.5 Kbps. A satellite-based aviation weather information system was developed to broadcast text and graphical weather information to aviation users at any altitude, anywhere in the U.S. NASA also investigated the use of state-of-the-art satellite digital audio radio systems (SDARS) for delivery of weather information. Initial tests over Africa used a GA airplane and the AfriStar satellite. Subsequent tests over the north Pacific used jet transports and the AsiaStar satellite. Early success and stimulation of the market by NASA-industry cooperative research and development efforts from 2000 through 2002 contributed to the development and deployment of first generation commercial systems including the Honeywell FISDL, WSI InFlight, and XM WX Satellite services. These first generation systems broadcast a set of weather products to the cockpit from the ground via satellite or terrestrial stations.

Weather dissemination data links for the next, or second, generation of AWIN systems have been developed and validated by laboratory and flight testing. Aviation data-link architectures were selected based on their ability to disseminate weather information during the en-route phase of flight. Three distinct operational architectures were addressed based on aircraft class and operational airspace: (1) U.S. national capability for regional and GA operations; (2) U.S. national capability for

commercial transport operations; and (3) global capability for transport operations. To be recommended as a viable solution, a data link had to demonstrate (1) transmission and reception of weather information without impacting "normal" traffic and (2) feasibility of an operational implementation. The validation of data links was accomplished through partnerships with FAA, industry, and academia.

5.1 Capability for GA and Regional Aircraft

The UAT system, previously selected by the FAA for GA Automated Dependent Surveillance Broadcast (ADS-B) services, was selected for development of a GA and regional weather dissemination capability. UAT equipment was modified and utilized to satisfy requirements for ground-to-air broadcast of weather information, air-to-ground delivery of atmospheric data from airborne sensors, and air-to-air reporting of weather hazard information to aircraft within range.

The necessary data link modifications were limited to the recognition and routing of additional messages not currently in the UAT standard traffic, and did not require a redesign of the UAT message formats and structures. Laboratory testing was conducted at the FAA Technical Center in 2004. Flight-testing during the spring of 2005 provided final validation of the weather dissemination capabilities. These tests used two NASA Lear Jets equipped with modified avionics and an operational UAT ground-based terminal installed at the Cleveland Hopkins International Airport, USA.

5.2 U.S. Capability for Transport Aircraft

Weather dissemination capability was developed for commercial transport aircraft operating in the U.S. national airspace that included ground-to-air reception and display of flight information services – broadcast (FIS-B) weather products, air-to-ground pilot weather information requests, dissemination of data from own-ship turbulence encounters to other aircraft and ground users, and delivery to the cockpit of turbulence reports from other aircraft. The FAA VHF Data Link Mode 3 (VDLM3) and 1090 Extended Squitter (1090ES) ADS-B data links were selected for development of this capability. VDLM3 was utilized for ground-to-air broadcast of weather information and air-to-ground reporting of turbulence encounters. VDLM3 also accommodated pilot requests for specific weather information not included in the basic ground-to-air broadcast and the subsequent augmented broadcast containing the requested information for a pre-determined period of time. 1090ES satisfied the requirements for air-to-air delivery of turbulence reports through broadcast to all aircraft within reception range.

Weather information from the ground to aircraft used a broadcast message. Although a VDLM3 ground-to-air broadcast capability exists by design, this mode of communication had not been implemented to date. Modifications included the enabling of Transport Control Protocol/Internet Protocol (TCP/IP) directly over VDLM3 in lieu of the Aeronautical Telecommunications Network (ATN) protocol stack in the Communication Management Unit and recognition and routing of messages not in the current VDLM3 standard planned traffic.

A turbulence encounter message was incorporated within the standard 1090ES message structure. Location, aircraft type, turbulence severity, and other required parameters needed for relevance processing on the receiving aircraft were broadcast directly (air-to-air) between aircraft. Location of the transmitting airplane was obtained from the ADS-B message.

Laboratory testing with VDLM3 avionics and ground stations and 1090ES avionics was completed in November 2004. Flight-testing providing final validation of VDLM3 and 1090ES weather dissemination capabilities was performed in 2005 utilizing two NASA Lear Jets equipped with modified avionics.

5.3 Global Capability for Transport Aircraft

A weather dissemination capability was developed for commercial transport aircraft operating in international and oceanic environments that included ground-to-air reception and display of FIS-B weather products, dissemination of data from own-ship turbulence encounters to other aircraft and ground users, and delivery to the cockpit of turbulence reports from other aircraft. The architecture selected used the Swift64 Multiple Packet Data Service mode via the Inmarsat satellite constellation.

For the international and oceanic environments, packet based, Inmarsat I3 services and capabilities were selected. Internet Protocol (IP) was chosen as the network protocol, and algorithms for seamless on-board separation of packet data services between cockpit and cabin were evaluated.

5.4 Future Weather Information Data Links

Weather dissemination technology progress has been significant but has relied on the innovative use of existing or planned data links. Weather data and information are expected to increase along with other communication demands for a new generation of air traffic control, safety, and security functions requiring a broadband link serving all aircraft. Cross-linking capabilities, increased ground and air data processing, and complex/flexible routing schemes must also be addressed in future communications systems. These future capabilities will only be realized if the equipment and services to support the networks and enabling data link are affordable. Broad user-based shared commercial systems, such as true aviation cellular and high value satellite communications, may hold the key to providing these needed capabilities at reduced cost.

6 Summary

Technologies have been developed by NASA in partnership with the FAA, NOAA, industry and the research community that enable more precise and timely knowledge of the flight environment and enable pilots in flight to make decisions that result in safer and more efficient operations. Technologies for first-generation data-link cockpit weather information systems have been developed and implemented. A second-generation system has been developed that can combine information from data-links and on-board sensors, evaluate weather hazards, and provide alerts. The capability has been developed to detect turbulence and display its severity up to 25nm ahead of commercial jet transports. Automated turbulence encounter reporting has been developed for commercial jet transports. Automated in-situ weather reporting has been developed to provide observations from aircraft to improve forecasting and identification of regions of hazardous weather. Data-link technologies have been developed that enable affordable and reliable broadcast of text and graphic weather products to the cockpit from the ground. Weather dissemination data links for the next-generation of systems have been developed and validated.

7 References

[1] Stough H, Shafer D, Schaffner P and Martzaklis K. Reducing Aviation Weather-Related Accidents Through High-Fidelity Weather Information Distribution and Presentation. *Proceedings 22nd International Congress of the Aeronautical Sciences*, Harrogate, UK, ISBN 0953399125, ICAS Paper ICA065iP, pp 651.1-651.13, 2000.

[2] Stough H, Watson J, Daniels T, Martzaklis K, Jarrell M and Bogue R. New Technologies for Weather Accident Prevention. AIAA 5th Aviation Technology, Integration, and Operations (ATIO) Conference, Arlington, VA, AIAA-2005-7451, 2005.

[3] Stough H, Watson J, Daniels T, Martzaklis K, Jarrell M and Bogue R. New Capabilities for Weather Accident Prevention. *Proceedings Flight Safety Foundation 58th Annual International Air Safety Seminar*, Moscow, Russia, ISSN 1528-4425, pp 251-270, 2005.

[4] Glenn Research Center. NASA Aviation Safety Program Weather Accident Prevention Project Annual Review, Williamsburg, VA, NASA/CP-2005-214031, 2005.

[5] Hamilton D and Proctor F. Airborne Turbulence Detection System Certification Tool Set. 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, AIAA 2006-75, 2005.